Colour vision: **Is colour constancy real?**

Anya Hurlbert

Colour constancy is typically weaker in the laboratory than it seems in our everyday experience. New measurements using real-world stimuli show that colour constancy is in fact almost perfect, and that several different perceptual mechanisms contribute to achieving it.

Address: Physiological Sciences, Medical School, Framlington Place, Newcastle upon Tyne NE2 4HH, UK.

Current Biology 1999, 9:R558–R561
http://biomednet.com/elecref/09609822009R0558

In his serial paintings of Rouen Cathedral, Monet portrayed dramatic changes in the colour of its western facade as the day progressed, from the misty blue of early morning to the orange-gold of evening. An ordinary observer would not perceive this shift to nearly the same extent, because of the phenomenon of colour constancy, a fundamental stabilising mechanism that compensates for changes in the colour of the light source in order to keep object colours constant. Monet's skills were not just in putting paint on canvas, but also in knowing how to disable this hard-wired feature of the human visual system.

The phenomenon of colour constancy presents an enticing theoretical problem. The light that an object reflects to the eye is the product of the object's inherent reflectance properties — which are constant — and the spectrum of the light source — which is variable. How does the visual system disentangle the two? Many candidate solutions have been proposed, which retrieve either the colour of the light source or the reflectance properties of the object. Yet we still do not know where or how colour constancy is achieved by the human visual system. Part of the problem is that we have not known the extent to which colour constancy really is achieved in the real world, but recent measurements using an ingenious technique promise to resolve that particular deficiency [1].

The ugly fact is that, in previous laboratory studies, colour constancy typically has not measured up to our everyday, subjective experience. Monet was an exception; we ordinary mortals live in the security that our blue coffee mug is blue indoors or out, under tungsten light or in sunshine. Yet experimental studies have recorded significant changes in colour appearance of surfaces under different illuminants [2–5]. What is the reason for this discrepancy? Is it because, subjectively, we mask the actual colour changes of objects with a colour that is fixed in our memory [6]? Or is it because the laboratory measurements were made with artificial images which lack the complexity and critical features of the real world that mediate colour constancy? A recent study by Kraft and Brainard [1] suggests that the latter is the correct answer.

For the past 20–30 years, 'Mondrian' images have been the stimuli of choice for colour constancy experiments (Figure 1). First introduced by Edwin Land [7] in his seminal demonstrations of the 'retinex' algorithm of colour constancy, Mondrian stimuli — collages of flat coloured rectangles — are works of abstract art in themselves. They do not, however, resemble real surfaces, which are typically curved or angled, shaded and textured, and so neither uniformly coloured nor uniformly bright. (Incidentally, it might be argued that the Mondrian stimuli used in such demonstrations are also misnamed, as they resemble better the more colourful work of Klee or Lohse). Furthermore, whereas Land constructed his large-field Mondrians from cuts of real coloured paper, most Mondrian stimuli are generated by computer and displayed on small screens. Such stimuli are even further removed from reality — the self-luminous patches of colour on the screen are qualitatively more similar to light sources than to surfaces.

The attraction of the computer display is that perceptually identical simulations of the light that reaches the eyes from real surfaces can be produced and precisely controlled. Observers can readily adjust colours on a computer screen — they cannot so readily adjust the colours of real objects. But in the computer simulation, surfaces and light sources are confounded and real cues may be lost. For example, one class of theoretical solution proposes that colour constancy may be achieved by using the information contained in specular highlights reflected from glossy surfaces, such as vegetable skin, paints, eggshells or plastics [8,9]. The highlights from these so-called inhomogeneous materials are almost perfect mirror reflections of the light source, and so their colour provides a clue to the colour of the light source. Similarly, mutual reflections — the light that surfaces reflect onto each other — contain information about the reflectance properties of the surfaces involved [10]. These cues are absent in Mondrian stimuli and therefore their potential contribution to colour constancy is lost.

One way to study the contributions of such cues would be to start with a simple stimulus and successively add cues, measuring each incremental improvement in colour constancy. Another way would be to start with the full stimulus and successively subtract cues. The latter is the

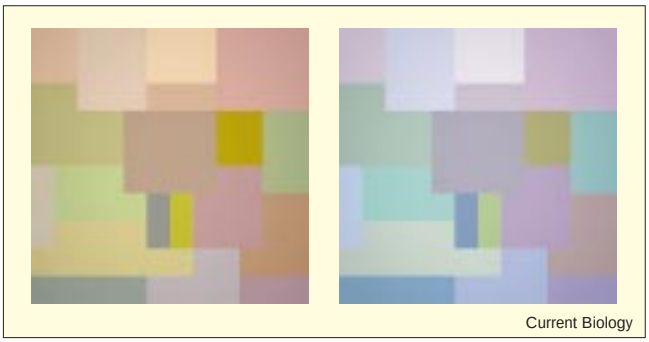
method employed by Kraft and Brainard [1]. In their experiment, observers looked through a window into a box containing papers and objects: a test surface against the back wall; a Mondrian-like panel of 24 different coloured papers; a tube wrapped in tin foil; and a cube, pyramid and tube made from grey cardboard (Figure 2). By clever design, this experimental chamber was endowed with advantages similar to those of a computer display: the colours of both the light source and the test surface could be finely adjusted.

The test surface was a rectangular piece of grey paper; the observer could, as if by magic, smoothly change the colour of the test surface by turning two knobs. These knobs controlled the colour of a rectangular patch of light exactly aligned with the test surface. The observer could not tell that the change in the colour of light reflected from the surface arose from a change in the light source targeted on the surface rather than from a change in the reflecting properties of the test surface itself. The rest of the scene was lit by a separate light source. By changing the colour of this light source, the experimentalists could achieve the effect of changing daylight on an outdoor scene, as well as many other illuminant changes.

The observer's task was to adjust the colour of the test surface to appear perfectly neutral (grey) under each new light source. For reference, the observers first adjusted the test surface to grey under a white light source. Perfect (100%) colour constancy would then mean that the observer would adjust the light coming from the test surface so as to have exactly the same spectral composition as that reflected from a piece of grey paper with the reflectance properties defined by the reference adjustment but now illuminated by the new light source. In other words, the same grey paper should look grey under every illuminant, even though it reflects a different spectrum of light in each case.

The first intriguing result was that the best colour constancy the observers achieved was 83%, for the scene with a full set of cues, in which the tin foil provided glossy highlights, and the various objects participated amply in mutual reflections. This measurement of colour constancy is probably the most accurate to date for vision in the real world, and it confirms the pre-existing suspicion that colour constancy is not entirely perfect. But there are a few caveats. The first is that, strictly speaking, the measurement applies only to the colour constancy of grey paper. The achromatic setting technique is a standard test for colour constancy, and it is assumed that it reveals the observer's internal assessment of the light source colour, and that this assessment applies to all coloured surfaces. But grey might be special — colour constancy might be better, or possibly worse, for other surfaces. (A recent study [11] has explored this question in detail.)

Figure 1



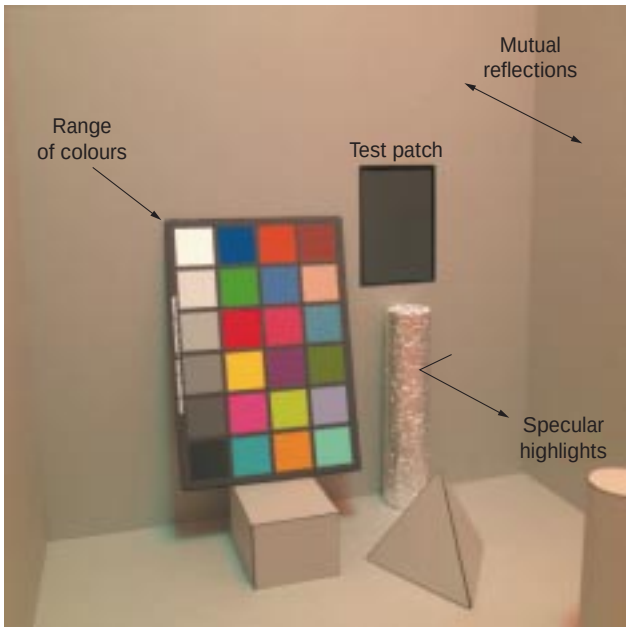
Typical 'Mondrian' stimuli: the same configuration of coloured papers is illuminated under yellowish daylight (left) or bluish daylight (right). To an observer viewing each scene separately, fully adapted and with perfect colour constancy, the two grey papers (third from the top on the left) would look identical.

The second caveat is that, although the real world is far better represented here than in most artificial images, it is still possible that the cues are not optimised. For example, theory suggests that glossy highlights will contribute most effectively when they arise from multiple, differently coloured, inhomogeneous surfaces [12]. In the experimental setup used by Kraft and Brainard [1], they arose from a single metal material — the tin foil. Still, 83% is a substantial level of colour constancy, and better than almost every other reported value. Which cues account for this high level of colour constancy? By successively silencing separate cues, Kraft and Brainard [1] found that they all made significant contributions.

Local contrast is probably the simplest, and yet one of the most powerful mechanisms proposed for colour constancy. The putative local contrast mechanisms takes the three retinal cone responses — red, green and blue — and transforms them into relative responses by comparing them with the cone responses to the immediate background. When the light illuminating the entire scene changes, from bluish to yellowish daylight, say, the amount of long-wavelength light reflected from both the test surface and its background will increase, but their ratio will stay the same [13]. The ratio of cone responses will also stay roughly the same, and so the encoded colour of the test surface will not change. Colour constancy is thereby achieved, at least for illuminant changes that preserve local contrasts.

Kraft and Brainard [1] subtracted the contribution of local contrast by creating two scenes, each under a different light source, carefully chosen so that in each scene the immediate background of the test surface reflected the same light. In the first scene, a grey background paper under a white light source combined to produce roughly neutral reflections, and in the second scene, the same

Figure 2



A real scene used by Kraft and Brainard [1] to study colour constancy. Potential cues for the recovery of the light source and intrinsic surface colours include mutual reflections between surfaces, specular highlights from glossy materials, and the mean and range of colours present in the scene.

reflections arose from a blue background under an orange-reddish light source. If local contrast were the whole story, the constancy index should have dropped to zero, and the observers should have adjusted the test surface to have the same colour in the two scenes, showing no compensation for the change in light source. But they did not do this. The observers adjusted the light coming from the test surface to be more orange in the second scene, as if their visual system discerned the orange colour of the light source, despite the lack of information from local contrast. But the constancy index did drop — it fell from 83% to 53%, suggesting that local contrast plays a substantial role in colour constancy.

Another potentially strong contributor to colour constancy is global contrast, in which local cone responses are compared with the average cone responses over the whole scene, not just from the immediate background. Global contrast is a natural extension of local contrast, and one that appears in many guises as a mechanism for colour constancy [7,14]. In the second scene above, global contrast would provide a weak but accurate cue to the orange colour of the light source. Might this cue fully account for the weak constancy observed? The answer is no. In the next experiment, the contribution from global contrast was silenced, while the contribution from local contrast opposed colour constancy. Now, the constancy index dropped even further, to 39%; but again, it did not drop to zero, showing that other cues must still be in force.

Lastly, when all accessory objects were removed from the scene, so that it contained no tin foil, no three-dimensional objects and no Mondrian panel, just the grey background and the single test surface, the observers still showed some residual colour constancy — the constancy index was 11%. This suggests a role for mutual reflections as the only remaining potential cue: the multiple reflections between the back wall and sides of the box may provide information about its inherent surface colour. That is, the blue box under orange light may be distinguished from a grey box under white light by the pattern of interreflections within it.

All the data, taken together, point to local and global contrast as the major contributors to colour constancy. It should actually be reassuring to us that local contrast is not the whole story: otherwise objects would noticeably change in colour when placed against different coloured backgrounds, even under the same illuminant. Global information from across the scene helps to balance any skew in the background colour particular to an object, ensuring that in a richly-appointed dining room a white plate on a red velvet cloth will look white, not green. It is clear from other studies of colour constancy that the range of colours in the scene, not just their global average, must also play a balancing role [15].

It also seems clear from recent studies of observers with deficits in colour vision that the local and global mechanisms operate at different levels in the visual system. The local contrast mechanism seems to be a primitive one, which takes place at early levels in the visual system: it is preserved even in an observer with the very rare disorder of cerebral achromatopsia, who cannot see colours at all as a result of temporo-occipital cortical lesions [16]. But as Ruettiger *et al.* [17] argued from their novel study of 27 patients, the global mechanisms vital for colour constancy most likely operate in higher-order visual areas. They found that certain patients with lesions of the parieto-temporal cortex had a normal ability to make colour discriminations on the basis of local contrast, yet failed on tests of colour constancy.

The study by Kraft and Brainard [1] marks a trend in vision science, a recognition that, because vision is adapted to the real world, the computer screen may be inherently limited for investigating perceptual mechanisms. This limitation is especially true for a phenomenon such as colour constancy, which is evidently not a single, simple operation, but the combined result of mechanisms that span the levels from sensation to cognition.

References

1. Kraft JM, Brainard DH: Mechanisms of color constancy under nearly natural viewing. *Proc Natl Acad Sci USA* 1999, 96:307-312.
2. Helson H, Judd DB: An experimental and theoretical study of changes in surface colors under changing illuminations. *Psych Bull* 1936, 33:740-741.
3. Arend LE, Reeves A: Simultaneous color constancy. *J Opt Soc Am* 1986, 3:1743-1751.
4. Troost J, de Weert C: Naming versus matching in color constancy. *Percept Psychophys* 1991, 50:591-602.
5. Lucassen M, Walraven J: Quantifying color constancy—evidence for non-linear processing of cone-specific contrast. *Vis Res* 1993, 33:739-757.
6. Beck, J: *Surface Color Perception.* London: Cornell University Press; 1972.
7. Land EH: The retinex. *Am Sci* 1964, 52:247-264.
8. Lee H-C: Method for computing the scene-illuminant chromaticity from specular highlights. *J Opt Soc Am* 1986, 3:1694-1699.
9. D'zmura M, Lennie P: Mechanisms of color constancy. *J Opt Soc Am* 1986, 3:1662-1672.
10. Funt B, Drew M, Ho J: Color constancy from mutual reflection. *Int J Comp Vis* 1991, 6:5-24.
11. Speigle JM, Brainard DH: The relationship between achromatic adjustment and asymmetric matching. *J Opt Soc Am A* 1999, in press.
12. Hurlbert AC: Computational models of colour constancy. In *Perceptual Constancy.* Edited by Walsh V, Kulikowski J. Cambridge, UK: Cambridge University Press; 1998:283-322.
13. Foster DH, Nascimento SMC: Relational colour constancy from invariant cone-excitation ratios. *Proc R Soc Lond B Biol Sci* 1994, 257:115-121.
14. Von Kries J: Chromatic adaptation. In *Sources of color science.* Edited by MacAdam DL. Cambridge, Massachusetts: MIT Press; 109-119.
15. Brown RO, MacLeod DIA: Color appearance depends on the variance of surround colors. *Curr Biol* 1997, 7:844-849.
16. Hurlbert AC, Bramwell DI, Heywood C, Cowey AC: Discrimination of cone contrast changes as evidence for colour constancy in cerebral achromatopsia. *Exp Brain Res* 1998, 123:136-144.
17. Ruettiger L, Braun DI, Gegenfurtner KR, Petersen D, Schoenle P, Sharpe LT: Selective color constancy deficits after circumscribed unilateral brain lesions. *J Neurosci* 1999, 19:3094-3106.